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Assessment of sustainable deficit irrigation in a Moroccan apple orchard as a climate change adaptation strategy

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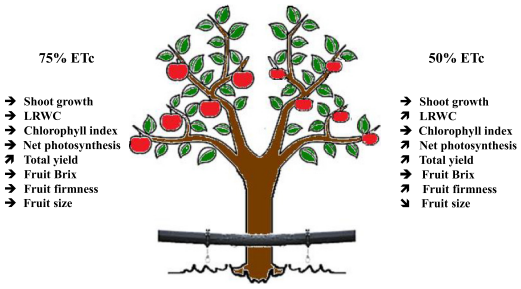
HIGHLIGHTS

- Mediterranean region is considered a "hot spot" for climate change.
- In many regions of Morocco, farmers overestimate plant water requirements.
- Smart irrigation for apple trees requires determination of a correct Kc.
- SDI of apple trees with 75% ETc shows an increase in crop yield.
- Fruit firmness increased with 50% of reduction of the applied water

GRAPHICAL ABSTRACT



Schema showing the effects of SDI (75 and 50 % ETc) in 2017 season on apple tree 'var. Gala'
(→ Unchanged, ↗ Increase, ↘ Decrease)

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ABSTRACT

This study was conducted over three consecutive years, 2015, 2016 and 2017, in the Imouzzer Kander region located in northwestern Morocco. The main objective is to evaluate apple tree responses to two sustainable deficit irrigation strategies with 75% (T2) and 50% (T3) of calculated crop evapotranspiration (ETc), compared to a control irrigated with 100% ETc (T1). During the three experiment years, estimated reference evapotranspiration (ET_0) was 630, 684 and 728 mm, respectively, in 2015, 2016 and 2017. Under the two restricted regimes, shoot length and fruit size evolution were not significantly affected. During the fruit set of 2017, no significant effects of sustainable deficit irrigation on the relative water content were observed, whereas they increased significantly during the fruit-swelling stage for the T3 treatment. Likewise, net CO_2 assimilation (A_n) was not affected by the irrigation dose, whereas it increased significantly and inversely proportional to the amount of applied water during fruit swelling. Thus, under our experimental conditions, the trees subjected to extreme deficit irrigation (T3) were not stressed at either stage. Moreover, deficit irrigation at 75% ETc increased apple yield significantly. In contrast, deficit irrigation at 50% ETc throughout the cycle was not enough to maintain an acceptable fruit size for the three studied campaigns. However, the best qualitative performance, notably for fruit firmness and sugar content, was attributed to this irrigation regime (T3).

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1. Introduction

The Mediterranean region is considered a "hot spot" of climate change. Several investigations (Abouabdillah et al., 2010; Amengual et al., 2012; Brouzyine et al., 2018; Senatore et al., 2010) warn of significant impacts on both mean precipitation and variability of hydrological processes, some papers predicting a 20% decrease in water availability. Morrocco, as an integral part of this area, is highly vulnerable to the adverse effects of climate change. Additionally, water and environmental resources, which are already under extensive pressure from population growth, industrialization, tourism and agricultural extension, are at particular risk (WB, 2017). Most predictions show that, over the coming decades, the country will gradually display signs of increasing aridity due to higher temperatures and reduced rainfall (Balaghi, 2017).

Agriculture is the largest water-consuming sector in Morocco, accounting for about 75% of water use in 2012 (MAPMDREF, 2015), utilizing around 10^6 hm^3 per year, while the demand expressed is about 5 billion m^3. It plays an important role in the economy and comprises approximately 14% of the national Gross Domestic Product, with significant annual variations (11–18%) depending on weather conditions during the growing season. Fruit trees, in particular the apple (*Malus domestica*), are a high water-demanding crop, thus dependent on irrigation, which raises questions about the sustainability of the country's apple production. Currently occupying >30,000 ha, it is the second most important rosaceous fruit species, following the almond crop. This requires the implementation of rational irrigation and new techniques for more efficient water use. With a share of 22% of national production, the apples are the main crop of the mountainous areas in the Fès-Meknès region. The most commonly used irrigation methods are still surface irrigation and micro irrigation-systems, covering 61 and 39% of the irrigated area, respectively (MAPMDREF, 2015).

Irrigation scheduling in horticultural orchards is based on an estimation of the reference evapotranspiration (ET_0), multiplied by a set of crop coefficients related to crop response (Allen et al., 1998). Worldwide, these coefficients have undergone several corrections. In 2012, the Food and Agriculture Organization of the United Nations (FAO) compiled new research studies on crop coefficients in its newsletter number 66 (Steduto, 2012). These published crop coefficients nevertheless need to be adjusted in function of real-use conditions. It is well documented that for certain crops maximum biomass production causes no stress, whereas for other crops, including trees, stress may not affect economic yields. In many cases, tree water status reaches its optimal value, horticulturally speaking, below a certain level of stress, and thus ETc must be multiplied by a stress factor (Ks), which is expected to change in the course of the season in accordance with the optimal tree-water status (Naor, 2010).

Moreover, in semi-arid areas, often characterized by increased evapotranspiration, high soil salinity and limited water availability, water-use efficiency needs to be increased (Lo Bianco et al., 2012). This situation requires that stricter irrigation control levels be tested which could save more water without sacrificing fruit-orchard productivity (Ro, 2001). It is therefore necessary to apply deficit irrigation in order to obtain a better ratio of irrigation-water quantity to optimum yield. In general, two types of deficit irrigation can be applied: 1) continuous water reduction throughout the entire crop cycle (SDI: Sustainable Deficit Irrigation), or 2) a targeted reduction during a given stage or period (RDI: Regulated Deficit Irrigation). SDI is generally applied to young plantations to assess the effect of possible moisture stress on vegetative growth and the fruiting of young trees (De Oliveira et al., 2017; Petillo et al., 2009; Treder et al., 2004; Ucar et al., 2016). This method can be also applied to adult orchards in order to readjust the predefined Kc models (Allen et al., 1998) based on actual orchard conditions (O'Connell and Goodwin, 2007; Naor et al., 2008; Sharma et al., 2003).

This paper discusses the effect of two levels of SDI on young apple trees. The underlying objective of the study is to readjust the Kc model, proposed by Girona et al. (2010), and published in the FAO bulletin 66, to the real conditions of the Imouzzer Kander region in Morocco.

2. Materials & methods

2.1. Experimental site and plant material

This study was conducted over three growing seasons (2015–2017) on a privately owned farm located at Imouzzer Kander in the Fès-Meknès region, Morocco (33°767′ Lat., −05°013′ Lon. and 900 m Alt.) (Fig. 1). Royal Gala' trees on M9 rootstock were planted in a north-south orientation in 2011 at a spacing of 1.25 m × 4 m and trained to the vertical axis system. The percentage of soil covered by tree canopy was 20, 25 and 30% for the first, second and third year of the experiment, respectively. The soil is a silty clay loam with 32% clay, 50% silt and 18% sand in the top soil (0–40 cm) which was expected to contain the effective root system considering tree age and the dwarf nature of the M9 rootstock. It has a water-holding capacity of about 166 mm in the top meter of the soil profile. During the three years of experimentation, average air temperature (°C) in the area was around 20 °C. The sum of reference evapotranspiration ET_0 during the irrigation season (from bud break to harvest) was around 630, 752 and 728 mm, respectively, for 2015, 2016, and 2017. Rainfall during the irrigation season was 70, 72, and 39 mm, respectively, for 2015, 2016 and 2017. Rainfall was considered in the allocation of irrigation water to each treatment. Except for the irrigation regimes (amounts of water) as described below, the trees were subject to the same farming practices such as fertilization, pest management, etc. The fruit thinning operation was carried out in the same way for all tree treatments.

The experiment plots were equipped with a localized drip irrigation system. Each planting line has a single polyethylene drip line (16 mm), equipped with integrated drippers uniformly spaced 60 cm apart on the drip line and delivering 1.6 l per hour. The irrigation dose was calculated using the following formula (1):

$$ET_c\ (mm) = (ET_0 * K_c) - \text{effective rainfall} \quad (1)$$

where ET_0 (mm) is the reference daily evapotranspiration calculated by the modified Penman-Montheith formula (Snyder et al., 1987). The estimation of ET_0 was based on climatic parameters obtained from the weather station installed on the farm, with Kc as the crop coefficient for apple trees proposed by Girona et al. (2010) (Table 1).

Effective rainfall consists of the amount of rainfall stored in the effective root zone and that lost by surface runoff, deep percolation or evaporation. The USDA SCS method (USDA, 1967) was used to estimate effective rainfall, taking into account the total rainfall corresponding to 80% of occurrence probability, the cultural evapotranspiration and the water available in the soil. In addition, a capacitance probe installed in the experimental trial was used to monitor the soil moisture at different layers so as to adjust the estimation of the total amount of water stored in the root zone after every rain or irrigation event.

2.2. Treatments and experimental design

Two SDI treatments were tested: irrigation with an application of 75 (T2) and 50% (T3) of ETc throughout the cycle. Trees irrigated with 100% of ETc were considered a control (T1). A randomized complete block design was used with four block replicates. Each block replicate housed the three treatments. Each treatment gathered 10 trees within the same block; three of them with the same trunk diameter were chosen for monitor parameters while the others were considered guard trees.

2.3. Irrigation and climatic conditions

In order to calculate the reference evapotranspiration required to schedule the irrigation for each treatment on a daily basis, all climatic

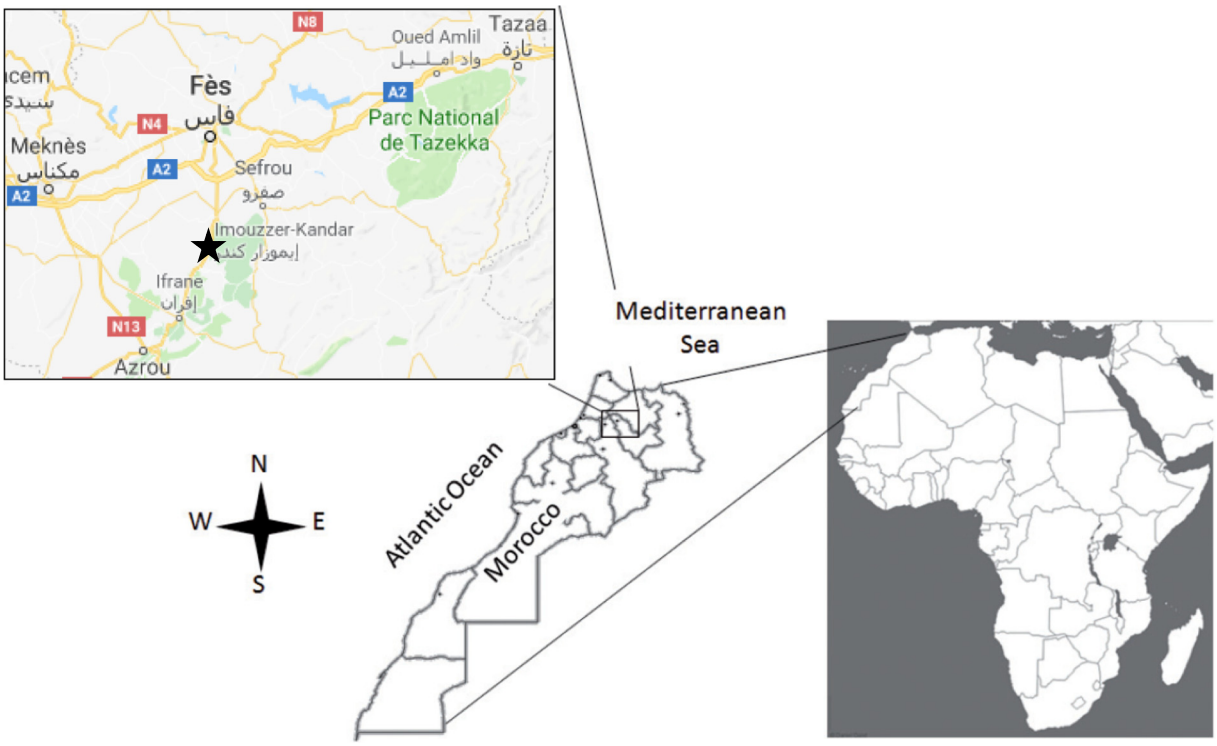

Fig. 1. Geographic location of experimental apple orchard (33°767' Lat., −05°013′ Lon. and 900 m Alt.) (Adapted from Google Maps).

parameters were used. Table 2 shows rainfall and the total quantity of reference evapotranspiration (ET_0) during the three irrigation seasons, and lists the total amount of irrigation water applied to each treatment.

Generally, the climate was completely different from year to year. During the period between flowering and harvest (130 days), the total ET_0 was increased by 54 mm between the 1st and the 2nd year and 44 mm between the 2nd and the 3rd year. In 2015, the first flower appeared on April 5th. The period of 60 days after flowering was characterized by regular rains. Due to a late cold snap in late March and early April 2016 and to the uneven temporal distribution of rains that year, flowering was behind schedule, beginning April 20th. As shown in Fig. 2, the first 15 days after flowering (DAF) in the 2nd year were characterized by an average ET_0 of 2.3 mm/day with 55 mm as a total precipitation amount. This cold period was followed by 20 hot days with an average ET_0 of 5 mm/day. The fruit-swelling period coincided with a very hot summer. The average ET_0 of this period, from the 65th to the 130th DAF, was 5.5 mm/day. In contrast, the third year (2017) was the driest, and the first flower appeared early on April 1st.

2.4. Plant measurements

Three trees per repetition (12 trees per treatment) were chosen for growth monitoring, yield and quality parameters. The trees were chosen based on trunk diameter in order to ensure homogeneity at the beginning of the experiment (coefficient of variation was 2%).

Table 1
Proposed K_c model for apple growing by Girona et al. (2010).

Stage	Days after flowering (DAF)	Kc
Flowering	0 to 25	0.45
Fruit set	26 to 65	0.65
Fruit growth	66 to 120	0.90
Maturation	121 to 130	0.70
Post harvest	131 to 190	0.50

2.4.1. Fruit size evolution and young shoot length and diameter

Fruit size evolution was monitored by measuring the diameter of two fruits per tree, born by two different branches located on either side of the main axis of the tree. Young shoot length (cm) and diameter (mm) were measured using a double decameter for the length and a precision caliper at the base of the twigs. Measurements were made weekly on three trees from each experimental unit.

2.4.2. Ecophysiological parameters

The ecophysiological parameters were measured only in the last season of the experiment (2017). Leaf gas exchange measurements were made in situ with a Li-COR 6400 portable photosynthesis system (LICOR-6400, LI-COR Biosciences, Inc., Lincoln, Nebraska, USA), connected to a 2 × 3 cm leaf chamber and a red-blue diode illuminator. Two measurement sets were first taken on May 19th, 2017 which corresponds to the 48th DAF (fruit set) and secondly on July 21st, 2017 which corresponds to the 111th DAF (fruit swelling). The CO_2 assimilation rate (A_n) was measured in relation to calculated internal leaf CO_2 concentrations (C_i), stomatal conductance (g_{sw}) and transpiration (T_r) were measured from 9:00 to 15:00 on two fully expanded leaves per tree, and on one tree per treatment in the same block at a photosynthetic photon flux density (PPFD) of 1500 μmol m^{-2} s^{-1}, at a leaf temperature of 28 °C and a CO_2 concentration of 400 μmol s^{-1}. These values are considered

Table 2
Climatic Balance sheet (reference evapotranspiration ET_0 and precipitation) and total amount of irrigation water applied to each treatment: T1 (control), T2 (75SDI and T3 (50SDI) for 2015, 2016 and 2017.

Seasons	ET_0 (mm)	Precipitation (mm)	ETc (mm)		
			T1	T2	T3
2015	630.1	70.6	437	328	218
2016	684.3	72.2	532	399	266
2017	728.0	39	519	389	259

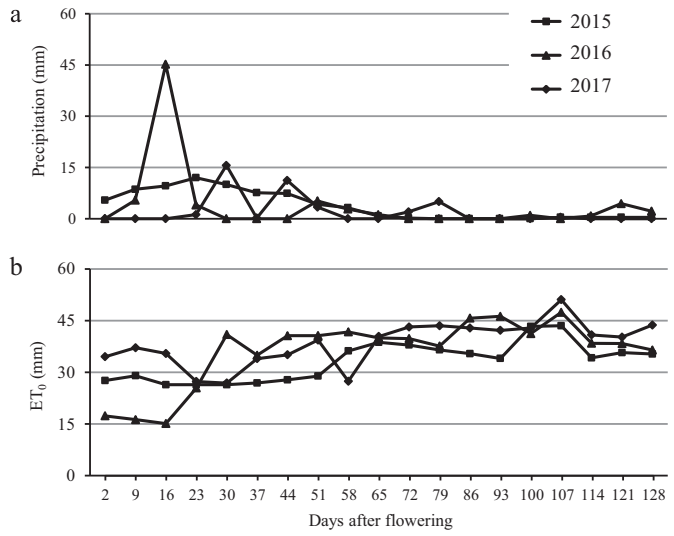

Fig. 2. Weekly Average (a) rainfall received by each trial plot and (b) reference evapotranspiration (ET_0) for 130 days following flowering for the years 2015 (■), 2016 (▲) and 2017 (◆).

a suitable reference for the apple case (Massonnet et al., 2007). Each step included 5 min for adjustment and stabilization followed by ten data logs at 1 min intervals.

The FieldScout CM 1000 NDVI, developed by Spectrum Technologies Inc. (360 Thayer Court, Aurora, IL, USA), was used to measure the Relative Chlorophyll Index (RCI) on both east and west sides of the tree, taking two measures each.

From each tree, two leaf samples were collected, on May 19, 2017 which corresponds to the 48th DAF (Fruit set) and on July 21st, 2017 which corresponds to the 111th DAF (Fruit swelling), while the Leaf Relative Water Content (LRWC) was estimated using the Eq. (2) described by Turner (1981):

$$\text{LRWC}\ (\%) = \frac{\text{FW}-\text{DW}}{\text{TW}-\text{DW}} * 100 \quad (2)$$

where: FW = fresh weight (g); DW = dry weight (g); TW = turgid weight (g).

2.4.3. Yield and quality parameters

During the trial years fruit was harvested on August 10th, 2015, on September 2nd, 2016 and on August 4th, 2017. The fruit yield per tree was determined for each of the 12 trees per treatment and the average yield was calculated for each treatment. The average fruit weight per tree was calculated using the yield per tree and the number of fruits per tree.

Fruit density, seed number, firmness (kg cm^{-2}) and total sugar level (°Brix) are the parameters used to evaluate the effects of SDI on fruit quality. Average fruit density (FD) (g cm^{-3}) (Eq. (3)) was determined through a sample of 9 fruits with different sizes per experimental unit, using the weight/volume relationship (3). The sample is weighed and placed in a container of known volume and then water is added to complete the volume to reach the container limit.

$$\text{FD} = \frac{\text{Wf}}{\text{Vf}} \quad (3)$$

where: Wf = fruit weight (g); Vf = fruit volume (the difference between the total volume and the added water volume) (cm^3).

The same samples were used to determine total sugar level (using a digital refractometer), fruit firmness (using a digital penetrometer) and seed number.

Finally, the apples were graded according to a commercial size grade ranging from 45 to 85 mm. The percentage of fruit in various size categories was determined as class A (>70), B (65–70) and C (<65 mm).

2.5. Statistical analysis

Values are expressed as mean ± standard deviation (SD) ($n > 4$). The results were analyzed using one-way analysis of variance (ANOVA) followed by Tukey's multiple comparison test using the software Graphpad Prism 5 (GraphPad Software, Inc.). A value of p below 5% ($p < 0.05$) was considered statistically significant.

3. Results and discussion

3.1. Growth parameters

The effects of SDI on growth parameters (shoot growth and fruit diameter) are presented in Table 3. The evolution of these parameters is shown in Fig. 3. During the three trial years, the three applied irrigation regimes did not show any significant effect on shoot length evolution, while for shoot diameter the results obtained show a significant effect of irrigation amount during the fruit-set stage. Indeed, trees receiving deficit irrigation treatments (T2 and T3), showed a lower significant evolution of shoot diameter compared to the control. This result aligns with the finding reported by Küçükyumuk et al. (2013), who examined the effect of water stress on the apple tree (Braeburn). Similarly, O'Connell and Goodwin (2007) demonstrated that no significant difference was observed in shoot length growth between the control and SDI treatments. Regarding fruit diameter, the irrigation regime effect during the fruit set and swelling stages is insignificant. This result is supported by the conclusions of O'Connell and Goodwin (2007) who showed that no significant difference was discerned between the treatments under SDI. However, another study, published by Mpelasoka et al. (2000), indicates that changes in fruit diameter increased with higher irrigation rates.

3.2. Ecophysiological parameters

Statistical analysis highlighted the absence of significant effect of SDI on the LRWC during the fruit set stage. In contrast, a significant effect was noted during the fruit swelling stage (Fig. 4). Indeed, T3 treatment had the highest (66%) LRWC during fruit swelling. The trees subjected to extreme deficit irrigation were, thus, not water-stressed under the conditions in either of these stages. It is well known that LRWC had a positive significant influence on net photosynthesis (Surendar et al.,

Table 3
Effects of Sustainable Deficit Irrigation (SDI) on vegetal parameter evolution (shoot diameter, shoot length and fruit diameter) of apple trees (var. Gala) during 2015, 2016 and 2017 in T1 (control), T2 (75SDI) and T3 (50SDI). Means ($n = 24$) in columns followed by different letters are significantly different at $p < 0.05$ based on Tukey multiple range test.

Seasons	Treatments	Parameters					
		Shoot diameter (mm $week^{-1}$)		Shoot length (cm $week^{-1}$)		Fruit diameter (mm d^{-1})	
		Fruit set	Fruit growth	Fruit set	Fruit growth	Fruit set	Fruit growth
2015	T1	0.99 a	0.44 a	2.57 a	0.97 a	0.38 a	0.72 a
	T2	0.63 b	0.35 a	2.60 a	0.65 a	0.39 a	0.67 a
	T3	0.45 b	0.25 a	2.63 a	0.44 a	0.41 a	0.70 a
2016	T1	0.40 a	0.16 a	0.95 a	0.45 a	0.46 a	0.60 a
	T2	0.33 b	0.15 a	0.88 a	0.32 a	0.40 a	0.59 a
	T3	0.32 b	0.14 a	0.83 a	0.24 a	0.45 a	0.57 a
2017	T1	0.61 a	0.39 a	1.85 a	0.98 a	0.37 a	0.74 a
	T2	0.57 ab	0.25 a	1.70 a	0.93 a	0.38 a	0.71 a
	T3	0.53 b	0.28 a	1.18 a	0.92 a	0.36 a	0.68 a

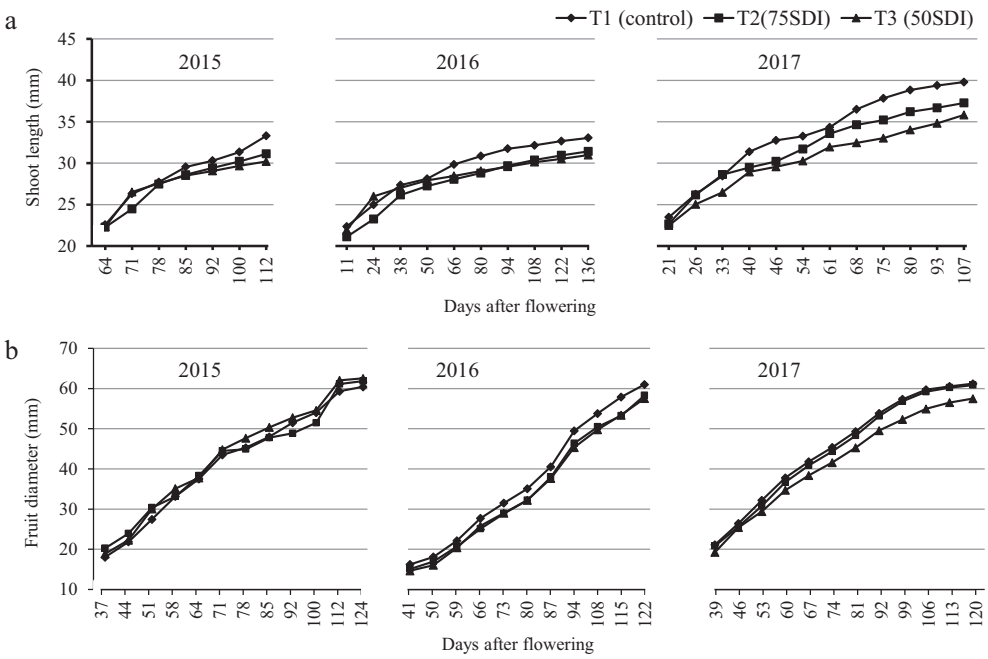

Fig. 3. Effects of Sustainable Deficit Irrigation (SDI) on (a) shoot length and (b) fruit diameter evolution of apples (var. Gala) during the 2015, 2016 and 2017 growing seasons in T1 (control: ◆), T2 (75SDI: ■) and T3 (50SDI: ▲). Each symbol represents the mean of 24 measured shoots.

2013). The effects of SDI on photosynthetic parameters in the two fruit development stages (fruit set and fruit swelling) are shown in Fig. 5. During fruit set, net CO_2 assimilation (A_n) was not affected by the deficit irrigation, while it increased significantly and was inversely proportional to the amount of applied water in the fruit swelling stage. These findings were in agreement with the results of David (2002), in which a positive correlation between LRWC and net CO_2 assimilation was observed. In addition, in the fruit swelling stage intercellular CO_2 (C_i) levels decreased significantly with T3 compared to the other treatments. Furthermore, stomatal conductance (g_{sw}) and transpiration rates (T_r) evolved in the same way. Indeed, significant increases were observed for these two parameters for T3. Our results do not match those of De Oliveira et al. (2017) who noted that the stomatal conductance increases for treatments receiving more water, also leading to a slight increase in photosynthetic activity and transpiration. As previously mentioned, this dissimilarity could be due to the fact that trees with the T3 treatment were not stressed during the measurement process. It could be assumed, on the contrary, that the excess irrigation water applied in the T1 treatment may induce a temporary stress in the trees due to a transient hypoxic condition within the root zone. Correspondingly, Silva et al. (2013) have emphasized that the temporary measurements of gas exchange do not reflect the real ecophysiological behavior of the stressed plant throughout the day, and therefore need to be assessed with caution.

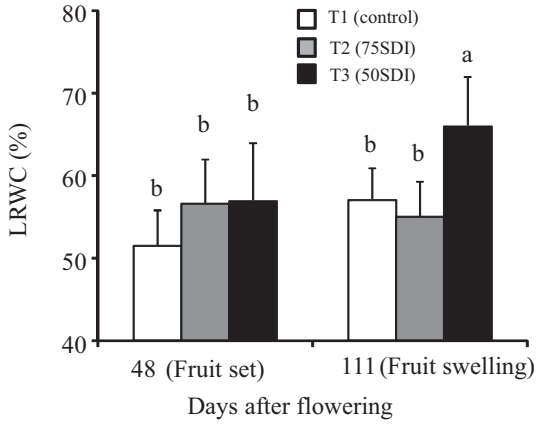

Fig. 4. Effects of Sustainable Deficit Irrigation (SDI) on leaf relative water content (LRWC) of apple tree (var. Gala) during 2017 growing season at two fruit development stages (fruit set and fruit swelling) in T1 (control), T2 (75SDI) and T3 (50SDI). Data represent the mean of 24 replicates; vertical bars indicate standard deviations. The different letters indicate significant differences according to Tukey test at $p < 0.05$.

The RCI data, presented in Table 4, indicate the absence of a significant effect of SDI. According to the first three measurement campaigns, the RCI means ranged from 436 to 550. These values are linked positively to the estimated reference evapotranspiration (ET_0). As expected, all plants presented a decrease in chlorophyll content with ageing. Thus, despite the increase in reference evapotranspiration (ET_0) during the last measurement (115th DAF), the RCI decreased significantly compared to the values obtained in previous measurement campaigns. Increased, decreased or unchanged chlorophyll content under deficit irrigation have been reported in the literature for many species (Bousba et al., 2009; Galindo et al., 2018; Mäkelä et al., 2000; Xu and Leskovar, 2014). However, it should be clearly stated that in nearly all research results, water stress generally induces a decline in chlorophyll content. This outcome was explained by Bousba et al. (2009) as a resistance strategy adopted by the plant to limit water loss by evaporation in order to raise resistance against the entry of the atmospheric CO_2 required for photosynthesis. Escalona et al. (1999) gave another explanation, assuming that the water-saving results in a relative turgor leads to a decrease in chlorophyll, and that within a biochemical limitation of the chloroplast to fix the CO_2, it probably associated with the limiting regeneration of Ribulose Biphosphate (RuBP).

3.3. Yield and quality parameters

In the first year of the experiment, no significant differences were observed between the three treatments concerning the total yield (Table 5). The yields were 25.7 t ha^{-1}, 26.3 t ha^{-1} and 26.4 t ha^{-1}, respectively, for T1, T2 and T3. In the 2nd year, the 50% reduction in irrigation water quantity led to a significant decline in the average yield of the T3 treatment trees (28.8 t ha^{-1}) compared to the control, while no significant difference was noted between the T2 (36.2 t ha^{-1}) and T1 (36.7 t ha^{-1}) treatments. In 2017, it was clearly shown that the applied

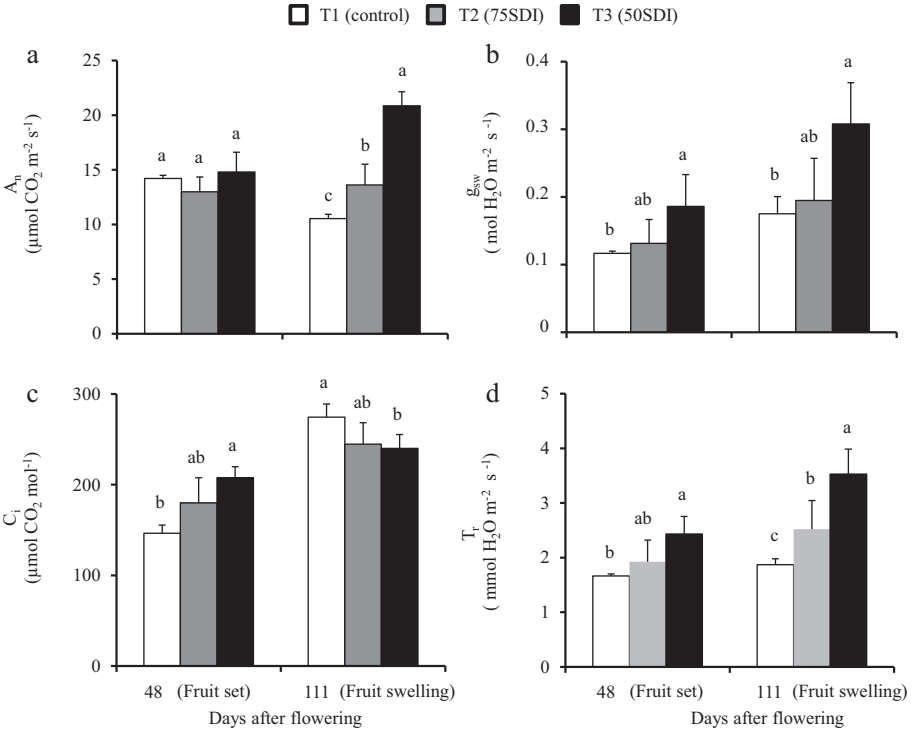

Fig. 5. Effects of Sustainable Deficit Irrigation (SDI) on CO_2 assimilation rate (A_n), stomatal conductance (g_{sw}), intercellular CO_2 concentration (C_i) and transpiration (T_r) of apple tree (var. Gala) during 2017 growing season at two fruit development stages (fruit set and fruit swelling) in T1 (control), T2 (75SDI) and T3 (50SDI). Data represent the mean of 20 values; vertical bars indicate standard deviations. Different letters indicate significant differences according to Tukey test at $p < 0.05$.

irrigation regime plays a crucial role in yield determination. The T2 treatment reached the highest average yield with 39.9 t ha^{-1}, followed by the T3 treatment with 34.7 t ha^{-1}, while T1 attained only 25.6 t ha^{-1}. The difference between the two extreme treatments T1 (control) and T3 (50SDI) can be explained by the instability of the climatic conditions, especially in the 2nd and the 3rd year. In fact, the 2016 growing season was characterized by some early cold weather and a very hot summer that led to a decline in yield for the T3 treatment that year. The early warm weather in the 3rd year (2017), resulting in a daily mean of ET_0 of around 5 mm/day in the flowering stage, probably generated high irrigation supplies to the T1 treatment during the flowering stage, whereas the trees did not require such amounts of water during this period. This overestimation of crop water requirements during this period resulted in a remarkable fruit drop for this treatment at the beginning of the fruit swelling stage, matching a very hot summer (The mean ET_0 was around 6 mm/day between the 65th and 130th DAF), (data not shown), which resulted in a yield decline.

A number of reports can be found in the literature providing different results on the effects of deficit irrigation on apple yield. Mpelasoka et al. (2001) concluded that a 50% water deficit throughout the entire cycle did not result in a significant loss in apple yield. In contrast, several authors (Küçükyumuk et al., 2013; Naor et al., 2008; Ucar et al., 2016) have reported that apple yield was positively correlated to irrigation water quantity. These conflicting results are probably due to varying experimental conditions (climatic, edaphic, cultivars, etc.) as well as to the irrigation scheduling method (irrigation frequency). Based on the above backgrounds, the reduction of 25% in irrigation water for our experiment, did not result in yield reduction. Contrary to expectations, yield increased significantly in 2017 compared to the control. It should be noted that a reduction of 50% could be beneficial in some cases where the climatic demand for water is not excessive.

Regarding the average fruit weight, the irrigation amount did not have an effect on this parameter during the 2015 and 2017 seasons. In contrast, the average fruit weight for all treatments in 2016 was lower than in the 1st and 3rd years of experimentation. This result can be explained by the unfavorable weather conditions. Moreover, in 2016, the T3 treatment showed a significant negative effect on average fruit weight compared to the control (T1). Mpelasoka et al. (2001) found that in water stress conditions of 50% ETc, the negative effect on fruit weight was significant compared to the 100% ETc treatment. Likewise, Ucar et al. (2016), working on the "Galaxy Gala" variety, and Küçükyumuk et al. (2013), working on the "Braeburn" variety, both concluded that fruit weight declines as irrigation decreases. Thus, our data from the 2nd year are consistent with the results of the three above-mentioned studies. This exception might be explained by water stress amplified by unfavorable

Table 4
Effects of Sustainable Deficit Irrigation (SDI) on relative chlorophyll index (RCI) of apple trees (var. Gala) during 2017 growing season at fruit growth stage with corresponding climatic parameters (total radiation (Rg), reference evapotranspiration (ET_0) and temperature average (T °)) in T1 (control), T2 (75SDI) and T3 (50SDI). Data represent the mean ± SD ($n = 48$). The different letters indicate significant differences according to the Tukey test at $p < 0.05$.

Days after flowering (DAF)	Global radiation (W m^{-2} d^{-1})	ET_0 (mm)	T° average (°C)	Chlorophyll index		
				T1	T2	T3
69	24,690	4.8	23.6	493.1 ± 67.6 a	443.8 ± 58.9 a	501.8 ± 71.4 a
81	34,325	6.2	23.4	550.6 ± 84.1 a	483.2 ± 34.7 a	494.3 ± 51.5 a
97	33,738	5.6	18.3	517.3 ± 74.3 a	436.7 ± 81.6 a	452.2 ± 62.4 a
115	33,165	6.5	25.4	323.3 ± 31.8 a	299.9 ± 42.3 a	324.1 ± 28.5 a

Table 5
Effects of Sustainable Deficit Irrigation (SDI) on production parameters (total yield and fruit weight) of apple trees (var. Gala) during 2015, 2016 and 2017 growing seasons in T1 (control), T2 (75SDI) and T3 (50SDI). Data represent the mean ± SD ($n = 4$). The different letters indicate significant differences according to the Tukey test at $p < 0.05$.

Seasons	Treatments	Parameters	
		Total yield (t ha^{-1})	Fruit weight (g fruit^{-1})
2015	T1	25.7 ± 2.1 a	159.5 ± 22.0 a
	T2	26.3 ± 0.7 a	157.6 ± 14.6 a
	T3	26.4 ± 1.2 a	154.1 ± 19.3 a
2016	T1	36.7 ± 2.4 a	110.7 ± 16.4 a
	T2	36.2 ± 2.6 a	110.4 ± 17.7 a
	T3	28.8 ± 2.2 b	101.6 ± 15.1 b
2017	T1	25.6 ± 3.0 b	157.8 ± 21.1 a
	T2	39.9 ± 4.5 a	184.0 ± 25.3 a
	T3	34.7 ± 3.2 a	142.3 ± 23.8 a

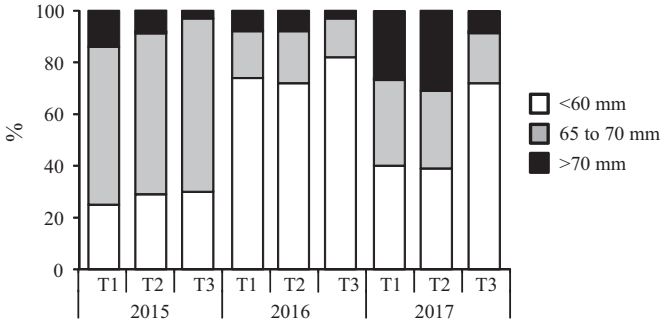

Fig. 7. Effects of Sustainable Deficit Irrigation (SDI) on apple fruit size distribution at harvest divided into three categories: <60 mm (white column), 65 to 70 mm (Grey column) and >70 mm (black column) during 2015, 2016 and 2017 seasons in T1 (control), T2 (75SDI) and T3 (50SDI). Values represent average of 12 trees per treatment.

climatic conditions, especially in the growing stage under a restricted irrigation regime (50% ETc).

Fig. 6 shows the relationship between volume, weight and seed number for the apples harvested in 2017. With the T3 treatment, though volume showed a significant correlation with fruit weight ($R^2 > 0.9$), no other significant difference was observed for fruit weight, despite the decreasing trends previously observed. In contrast, with the T2 treatment, which also produced the largest fruit, volume increased linearly along with the number of seeds per fruit. However, seed number alone cannot explain this result. As highlighted in Fig. 7, fruit size distribution did not differ between the T1 and T2 treatments in the last year of study. Thus, a 25% water reduction did not affect the fruit caliber profile. In contrast, with an irrigation water deficit of 50% ETc, a reduced fruit size was observed. This result is consistent with those obtained by Küçükyumuk et al. (2013) and Naor et al. (1995), showing that deficit irrigation leads to significantly lower fruit size. In 2016, >70% of fruit from all three treatment regimes were of a smaller caliber (<60 mm), which, as mentioned above, may be explained by unfavorable climatic conditions.

The data in Table 6 shows the measured fruit quality parameters (°Brix, firmness, seed number and density) of the fruit at harvest. Deficit irrigation had no significant impact on fruit density or seed number. In contrast, the reduction of 25 and 50% ETc had an important effect on °Brix increase during the 1st and the 2nd years, contrary to the 3rd year where no significant effects of water regime were observed. The results of the first two years of study are consistent with the findings of Chenafi et al. (2016) who showed that, compared to the comfort irrigation treatment, the apples produced under deficit irrigation have a high °Brix. Similar results were also obtained by De Oliveira et al. (2017), Küçükyumuk et al. (2013), Mpelasoka et al. (2000) and Naor et al. (1995). Ucar et al. (2016), on the other hand, reported that the °Brix for the Gala Galaxy apple variety under water stress was not significantly different from the 100% treatment. In the first two years of study, the deficit irrigation did not significantly affect fruit firmness, even though the average values were higher compared to the control (T1). This increase was significant during the third year for the trees under T3. Several authors (Chenafi et al., 2013; Küçükyumuk et al., 2013; Mpelasoka et al., 2001) have shown that the treatments under deficit irrigation had higher firmness values, which may be explained by an increase in cell density due to the fruit size reduction (Ebel et al., 1993).

4. Conclusion

Accurate measurements of crop coefficients (Kc) are needed for sustainable irrigation scheduling of fruit trees in irrigated areas. In this study, two sustainable deficit irrigation regimes (75% and 50% ETc) were assessed and compared to a control treatment (100% ETc) over the growing seasons of 2015–2017, on apple trees (var. Gala). On the one hand, in our conditions, all the monitored parameters indicated that a continuous water reduction of 25%, compared to fully irrigated control with 100% ETc, had no significant negative effect. This reduction even slightly improved some yield parameters (total yield, fruit weight and caliber profile), and quality parameters (firmness and °Brix) of the apple trees. On the other hand, an SDI at 50% ETc throughout the entire cycle was insufficient to maintain an acceptable fruit size for the three studied campaigns. However, the best qualitative performance, notably fruit firmness and sugar content was attributed to this irrigation regime. Additionally, it was found that the decrease in yield and fruit caliber began in the warm period, which coincides with the fruit growth stage. Based on this result, it can be concluded that it is possible to adjust the Kc model for the treatment receiving 50% ETc by increasing this crop

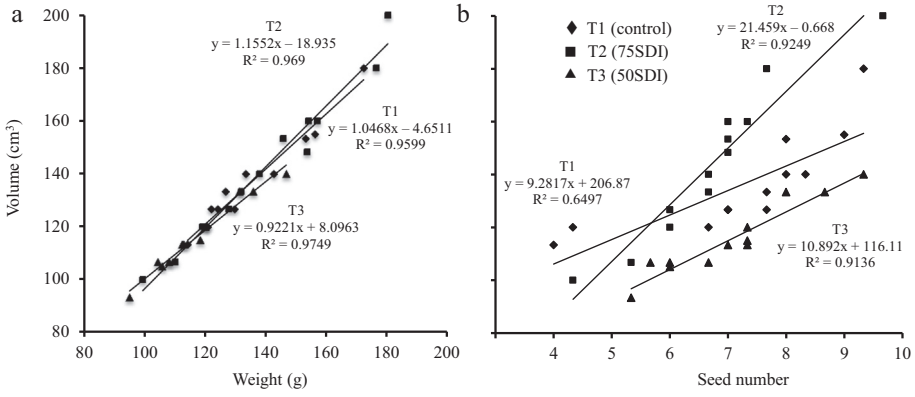

Fig. 6. Relationship between weight and volume of apples harvested during 2017 season in T1 (control:◆), T2 (75SDI:■) and T3 (50SDI: ▲). Each symbol represents mean of 3 measured fruits.

Table 6
Effects of Sustainable Deficit Irrigation (SDI) on fruit quality parameters (Brix°, firmness, seed number and density) of apples (var. Gala) harvested during 2015, 2016 and 2017 seasons in T1 (control), T2 (75SDI) and T3 (50SDI). Data represent the mean ± SD ($n = 36$). The different letters indicate significant differences according to the Tukey test at $p < 0.05$.

Seasons	Treatments	Parameters			
		Brix°	Firmness	Seed number	Density
2015	T1	14.1 ± 0.1 b	4.4 ± 0.1 a	nd	nd
	T2	14.9 ± 0.2 a	4.5 ± 0.1 a	nd	nd
	T3	15.0 ± 0.2 a	4.6 ± 0.1 a	nd	nd
2016	T1	14.4 ± 0.2 a	4.1 ± 0.2 a	6.4 ± 2.1 a	6.4 ± 2.1 a
	T2	14.5 ± 0.3 a	4.2 ± 0.2 a	7.6 ± 2.3 a	7.6 ± 2.3 a
	T3	15.0 ± 0.4 b	4.3 ± 0.2 a	6.4 ± 2.0 a	6.4 ± 2.0 a
2017	T1	14.4 ± 0.4 a	5.3 ± 0.3 b	6.7 ± 2.2 a	6.7 ± 2.2 a
	T2	14.5 ± 0.3 a	5.5 ± 0.3 b	7.2 ± 1.9 a	7.2 ± 1.9 a
	T3	14.8 ± 0.4 a	5.9 ± 0.2 a	7.1 ± 2.6 a	7.1 ± 2.6 a

coefficient during the fruit growth stage. This suggestion will help to save irrigation water without affecting the production and the quality parameters.

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